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SOME ISSUES RELATED TO THE
THEORY OF TROPICAL CYCLONE MOTION

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<p>A summary of key issues is presented based on the discussions at a Planning Meeting on the Theory of Tropical Cyclone Motion held in Monterey, CA during 29-30 July 1986. The purpose of this summary is to demonstrate that this is a fruitful area of research and to encourage participation in a five-year basic research program sponsored by the Office of Naval Research. A method of defining the cyclone and the environment in such a way as to highlight the associated nonlinearities is proposed based on the observational studies of G. Holland and recent theoretical results of H. Willoughby. Further studies of the beta-effect in relation to the shape of the wind profile in outer regions are needed. Other issues related to the form of the vortex and the role of physical processes in the cyclone are also suggested. Treatment of environmental structure effects such as vertical and horizontal shears is considered to be a necessary step to advance the theory. Extensions of ideas from recent studies of cyclone-cyclone interaction are proposed to study tropical cyclone-midlatitude trough interactions during the recurvature periods. Some hypotheses that might be tested in the observational component of the program</p>					
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Several members of the Department of Meteorology assisted in hosting the Planning Meeting. The very special local arrangements were the responsibility of Ms. Ellen Saunders. Mr. T. C. Yeh assisted in the recording of the sessions. Typing of the materials for the meeting and of this summary were expertly done by Mrs. Penny Jones.

Comments by Greg Holland, Terry Williams, Mike Fiorino, Hugh Willoughby, Mark DeMaria and Jim Peak on a draft of the summary report are gratefully acknowledged.

1. Introduction

A five-year accelerated research initiative to improve basic understanding of tropical cyclone motion will be funded by the Office of Naval Research (Marine Meteorology) beginning 1 October 1986. This initiative includes theoretical, observational and experimental components. The field experiment will be in the western North Pacific Ocean during the 1989 (or possibly 1990) typhoon season. Although the planning for the field experiment has not been started, it is expected that the existing operational resources will be supplemented by special aircraft and satellite observations. New instrumentation such as doppler radar and buoys may also be involved.

The first step in the planning for the research initiative was an informal Planning Meeting on the Theory of Tropical Cyclone Motion held in Monterey, CA on 29-30 July 1986. The meeting was organized on rather short notice to take advantage of several Australian and USA meteorologists being in California for another meeting (see attendance list in Appendix A). Unfortunately, many other USA and international scientists interested in tropical cyclone motion studies could not attend. This report is an attempt to summarize the results of the meeting in such a way as to promote interest and participation in the research initiative by these scientists. This summary cannot reproduce the stimulation and understanding that comes with exchanges of ideas that occur on a personal basis. Nevertheless, it is hoped that recording some of the key issues will convince the readers that this is a fruitful area of research. Inquiries and comments of a scientific nature should be directed to the author, who is the Scientific Director. Questions regarding administrative aspects or the possibilities for funding research should be sent to Dr. R. Abbey (address in the Distribution List).

The purpose of the Planning Meeting was to explore the present status of our theoretical understanding of tropical cyclone motion for the purpose of defining the theoretical component of the overall research initiative. Thus, the goal was to describe the key issues that need to be addressed during the next 3-5 years to advance our theoretical understanding. A list of discussion questions was prepared in advance (Appendix B). Although there is considerable overlap in these questions, the resulting discussions are summarized in Section 3 with a similar organization. Some suggested research approaches are listed in Section 4. To promote interactions with the observational component of the research initiative, some testable hypotheses that arose during the discussions are grouped in Section 5. Finally, a few possibilities for applying the theoretical results to the problem of track forecasting are given in Section 6.

2. State-of-the-Science

Reviews of the theory of tropical cyclone motion are available in the monograph by Anthes (1982) and in the section written by G. Holland for the International Workshop on Tropical Cyclones (IWTC) in Bangkok, Thailand. This material will be contained in a forthcoming book based on the materials prepared for the IWTC (Elsberry, 1986).

Although the Planning Meeting was not intended to be a forum for conference-type presentations, some results based on research-in-progress were described. Manuscripts have been submitted in some cases and others are in preparation. Consequently, it is not appropriate to discuss these results in detail here. Rather, only some brief highlights will be presented.

J. C.-L. Chan and R. T. Williams of the Naval Postgraduate School (NPS) have described the tropical cyclone translation due to the beta-effect in terms of an interaction between the linear effect distorting the vortex and the nonlinear centripetal acceleration attempting to restore symmetry in the vortex. Their numerical simulations produce an isotach maximum (minimum) on the right (left) side of the vortex. This asymmetry exceeds that expected from the linear superposition of a symmetric vortex and a basic current. A northwestward drift on the order of 500 km in 72 h is predicted in a no basic flow environment. However, this displacement is highly dependent on the wind profile beyond some critical radius that exceeds 100 km, which confirms earlier work by Kitade (1981) and Holland (1983).

M. Fiorino of the Naval Environmental Prediction Research Facility (NEPRF) has used the same barotropic, non-divergent model as Chan and Williams to study the effect of vortex structure on tropical cyclone motion. Fiorino has compared the "residual current" (after subtraction of the vortex signature) with the actual cyclone motion. Within a small region near the

center, this residual current is toward the northwest, whereas the average over a larger domain is toward the north. Thus, the residual current has a spatial structure. It was unfortunate that M. Mathur of the National Meteorological Center could not attend and present his recent studies on the role of the vortex structure on hurricane prediction.

H. Willoughby of the Hurricane Research Division (NOAA) has developed a new dynamical model framework to study the interaction between the forced asymmetric structure and the motion of the tropical cyclone. The forcing, which may be due to embedded convective cells, steering currents or the beta-effect, interacts with the motion through the wavenumber one asymmetry. Dynamically, this asymmetry appears to be a trapped Rossby wave that depends upon the radial gradient of relative vorticity. For example, a convective source/sink pair that rotates around the cyclone center with a frequency near the local orbital frequency of the mean axisymmetric flow can both excite these Rossby waves with large amplitude and induce motion of the cyclone as a whole. This mechanism provides a plausible explanation of the trochoidal track oscillation. For each of the forcing mechanisms studied, the solutions after removal of the axisymmetric vortex resemble the solitons described by quasigeostrophic theory.

Research aircraft observations in Atlantic hurricanes reveal a circulation similar to the solutions, but the flight data depict only the inner 150 km of a pattern whose characteristic scale seems to be 5000-1000 km. At the 85 kPa level, the pattern tends to be oriented geographically rather than with the cyclone motion and comprises an anticyclonic gyre to the north of the center and a cyclonic gyre to the south (Fig. 1c). The resulting "ventilation" flow from east to west across the center is similar to the "residual flow" in Fiorino's study. Because of the fixed geographical

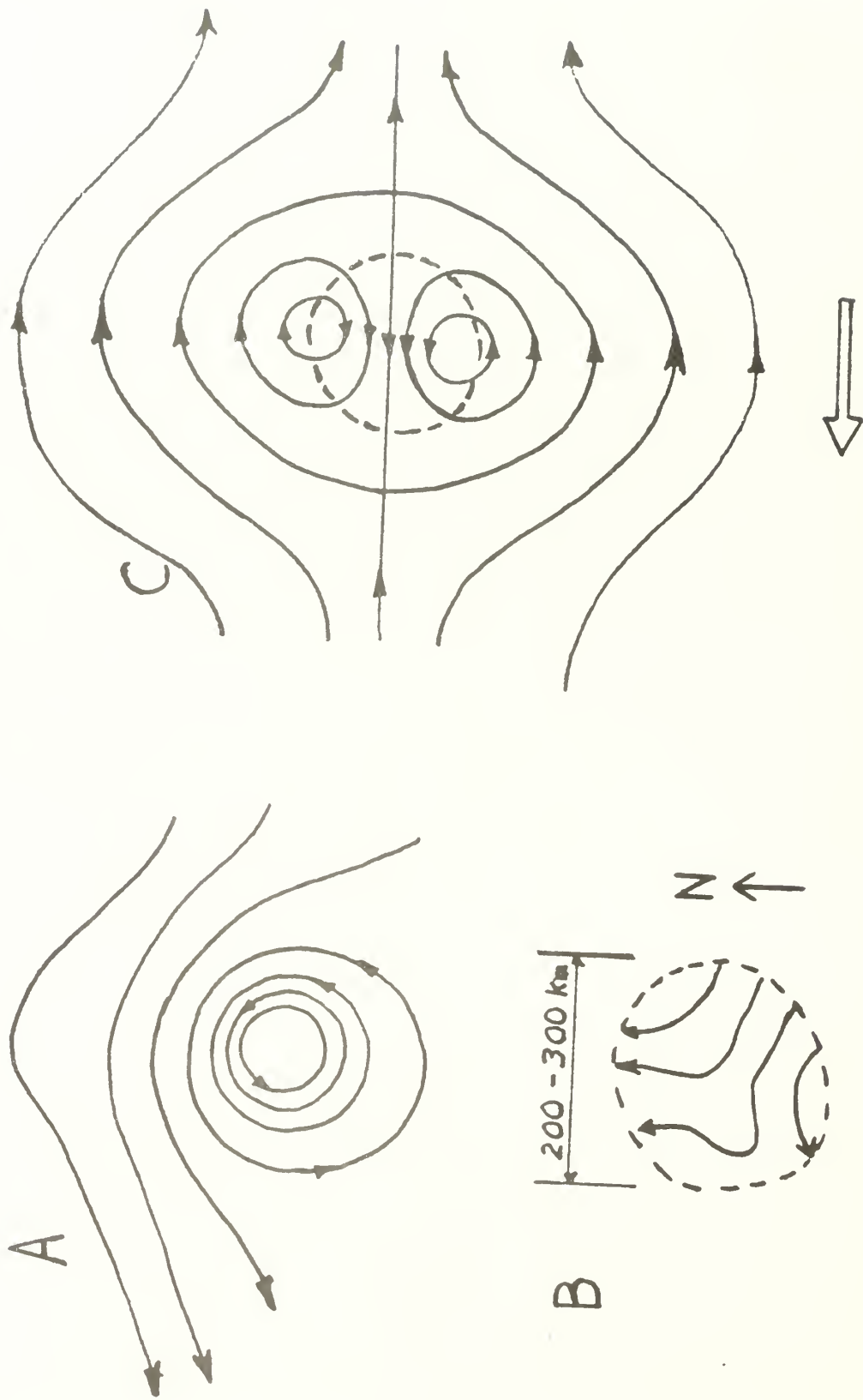


Fig. 1. Schematic illustrations of: (a) total streamfunction in a tropical cyclone; (b) observed streamfunction after subtraction of the axisymmetric vortex; and (c) theoretically-derived large-scale streamfunction. The streamfunction pattern (b) tends to be oriented geographically as indicated, whereas that in (a) and (c) is oriented with the relative motion between the cyclone and the environment. Thus, the observed pattern arises when the vortex moves westward through the surrounding flow. The domain within the dashed circles in (b) and (c) is 150 km in radius (based upon Willoughby *et al.*, 1984, and additional unpublished research by H. Willoughby).

orientation, it is tempting to conclude that the gyres are a manifestation of the westward propagation of the cyclone under the beta-effect. However, the solution for the beta-effect alone has northward (rather than northwestward as in Chan and Williams) motion and fails to reproduce the observed orientation of the gyres. Thus, the observed pattern probably arises from the relative motion of the cyclone through the environment under the influence of westerly vertical shear.

G. Holland of the Bureau of Meteorology (Australia) described observational studies of the effect of tropical cyclone intensity on the motion. The statistical distributions of the zonal or the meridional motion components appear to be similar regardless of the intensity (minimum central sea-level pressure) of the storm. In particular, more intense storms do not seem to have a larger zonal/meridional component. However, research (manuscript received too late to be discussed) by Keqin Dong of the State Meteorological Agency of the People's Republic of China suggests that tropical cyclones that have already recurved into the westerlies do have larger zonal and meridional components with increasing intensities. An unresolved question (G. Holland, private communication) in Dong's study is whether these storms that have recurved are also larger in size, which could account for the larger translations.

M. DeMaria of North Carolina State University has continued his studies of cyclone-cyclone interaction (see Chang, 1983; DeMaria and Chan, 1984; Dong and Neumann, 1983). The critical separation distance appears to be related to the radius at which the relative vorticity gradient changes sign. Another cyclone that is located within this radius will be attracted, whereas a cyclone outside this radius will be repelled. Thus, the focus is on the shape of the wind profiles at larger radii, which is consistent with the beta-effect studies mentioned above.

3. Key questions and issues

The discussion sessions were organized within seven categories (Appendix B). However, considerable overlaps occurred as the discussion freely ranged over the topics. No consensus was reached as to the priorities related to the theoretical studies of tropical cyclone motion. The following summaries are based (as interpreted by the organizer) on the summaries that the discussion leaders presented at the final plenary session.

a. Definition of cyclone versus environment. (G. Holland and R. Merrill)

It is generally accepted that a substantial component of tropical cyclone motion is associated with the large-scale environmental flow. However, no unique separation between "cyclone" and "steering current" has been established. The vorticity equation can be expressed in terms of cyclone (C) and environmental (E) effects in the form

$$\frac{\partial \zeta}{\partial t} = -W_E \cdot \nabla \zeta_C - W_C \cdot \nabla \zeta_E - W_E \cdot \nabla \zeta_E - W_C \cdot \nabla \zeta_C - \beta V + (f + \zeta) \nabla \cdot W.$$

Even though the numerical studies described in Section 2 begin with a symmetric vortex and a uniform (usually no flow) basic current, an asymmetry develops. Is this asymmetry to be attributed to the cyclone or to the environment (the "residual current" above)? If the cyclone is assumed to be symmetrical, the fourth term on the right will be zero. Near the cyclone center, the second term will clearly be much larger than the third term. In a no initial basic current case such as Chan and Williams treated, the first term will be zero at the beginning. However, the development of the "residual current" may also be interpreted as an environmental advection effect (first term). An alternate interpretation is that the cyclonic circulation advects the vorticity associated with the residual current (second term).

Another problem in these definitions is that there is not a clear separation in the horizontal scales of the cyclone and of the environment. In the region of a monsoonal trough, a distinction between the cyclonic circulation associated with the tropical cyclone and the large-scale horizontal shear is difficult to achieve.

A three-component system is proposed: (i) symmetric cyclone; (ii) background flow obtained by filtering out the cyclone scales; and (iii) remaining flow arising from interactions between the cyclone and the background flow. There are both mathematical and physical advantages in representing the cyclone as a symmetrical circulation. In the previous two-component system, (ii) and (iii) would have been combined in an asymmetric background flow that included cyclone components. In the proposed system, a filtered background flow is removed and the asymmetric cyclone scale component is contained in (iii). An example of such a pattern is shown in Fig. 1c.

Since specification of the "cyclone scale" and the filtering technique for deriving (ii) are somewhat arbitrary, these definitions will be study dependent. For example, the background flow may be horizontally uniform (i.e., equal to mean direction and speed of the tropical cyclone), or the horizontal shear may be included. Regardless of the definitions, the key idea is that both observational and numerical studies suggest an additional asymmetry beyond that due to superposition of the vortex and the background flow. Understanding the distinctions and interactions between (i), (ii) and (iii) should improve our ability to predict tropical cyclone motion. Moreover, we need to understand what synoptic situations are critically dependent on data so that the necessary observations are obtained in the critical areas.

b. Beta-effect on cyclone motion. (R.T. Williams and J. Jarrell)

Studies of the beta-effect have been a useful first step because

of the linearity of the problem. However, the Chan and Williams study illustrates the crucial role of the nonlinear terms in the northwestward displacement of the vortex. Nevertheless, a better understanding of the physical mechanism for the beta-effect propagation is desirable. How are the observed distortions of the outer region transmitted into the inner region to move the high vorticity region at the center? How does the effective radius depend on the shape of the wind profile, or the "strength" of the storm (as defined by W. Gray and associates at Colorado State University)? These questions lead directly to the next topic.

c. Form of the vortex. (M. Fiorino and J. Chi)

Much literature exists on the shape of the wind profile in the inner regions of tropical cyclones (Riehl, 1963; Shea and Gray, 1973; Anthes, 1982). The tangential (v) wind profile outside the radius of maximum winds (RMW) is often expressed as $vr^x = \text{constant}$, where $x = 0.5 \pm 0.3$. However, this profile often applies to only 3-4 RMW (typically 100-150 km). The vorticity near the center is proportional to the maximum wind divided by RMW. Although the curvature of the low-level flow remains cyclonic to greater distances, the wind shear is anticyclonic outside the RMW. Thus, the relative vorticity decreases rapidly with radius. From the circulation theorem, the relative vorticity must become negative if the vortex has finite horizontal extent, and it may become negative even in an unbounded vortex.

The beta-effect studies cited above indicate that the effect on the motion depends strongly on the shape of the wind profile in the outer regions. Willoughby's study, which allows weak anticyclonic flow at the periphery of the vortex, indicates northward motion when the relative angular momentum integrated over the vortex is cyclonic, southward motion when it is anticyclonic, and no meridional motion when it is zero.

Inner core asymmetries in the vorticity field are also important for

higher frequency oscillations in the storm track. These inner asymmetries may arise from internal processes, such as convection (as in the Willoughby study), or from external forcing through nonlinearities.

In summary, both theoretical and observational studies are needed to understand the effects of the vortex shape on tropical cyclone motion.

d. Physical processes and cyclone motion. (H. Willoughby and R. Smith)

The new model by Willoughby treats the tropical cyclone motion in terms of how the physical processes affect the azimuthal wave 1. One interpretation of the dynamics of the azimuthal asymmetry is in terms of a free Rossby wave. Other waves, such as gravity modes, may be involved as well. The key question is how these waves may be forced by convection, environmental divergence, surface friction, etc. Vertical shear in the environment may initiate the waves through baroclinic interactions. Horizontal shear in the environment may initiate the waves through barotropic interactions. For example, horizontal shear in the environment may generate azimuthal mode 1 and then interact nonlinearly with wave 2 or higher waves.

A question that will ultimately be important for numerical prediction models is the horizontal and vertical grid increments required to resolve accurately these processes. Willoughby's model has a 5 km horizontal resolution, and it appears that 9-10 km may be an upper limit. This has serious implications in terms of computer resource requirements and in regard to our ability to observe the specific characteristics of each tropical cyclone.

The theoretical ideas embodied in the pattern in Fig. 1 can provide a basis for analyzing how tropical cyclone motion occurs. Further theoretical studies relating the amplitude/horizontal scales of this pattern to different physical processes such as asymmetrical convection, wind distributions, frictional processes or the beta-effect are clearly desirable. One outcome of

the theoretical studies might be a specification of the most important aspects of the physics that will be required for accurate motion prediction. The model framework proposed by Willoughby appears to facilitate treatment of this question.

- e. Environmental structure effects on motion. (J. McBride, W. Gray, T. Keenan, W. Frank)

Much of the existing theory of tropical cyclone motion is based on barotropic models, usually with horizontally uniform basic currents. Advances in the theory require inclusion of the vertical (and horizontal) shear of the cyclone and of the environment. A key question is the role of baroclinic processes versus barotropic processes in the movement of the cyclone center. It is well-recognized that tropical cyclones preferentially form in the weak vertical shear regions of the monsoonal troughs. However, the remainder of the life cycle may include penetration of regions with considerable shear, such as near the subtropical ridge, and recurvature into the strongly sheared westerlies.

The most important track forecast problem is whether impingement of the upper-level westerlies will bring about recurvature. This question clearly requires a treatment of horizontal and vertical shear effects. From an observational perspective, we need to know what variables need to be measured to monitor the interaction of the tropical and midlatitude systems.

Interactions between the tropical cyclone and the subtropical or midlatitude systems may significantly change the vertical shear. According to T. Keenan, a very accurate prediction of the adjacent subtropical ridge is crucial in Australian cyclone predictions. This is a two-way interaction process, especially in recurvature cases. Another example is the interaction of the tropical cyclone with an approaching midlatitude trough, which may trigger an instability that could affect the penetration of the trough into the

tropics. Clearly, these are situations in which vertical (and horizontal) shear changes in time. The divergent component of the wind field will also be an important consideration in these cases.

The horizontal shear of the environment produces an effect similar to the beta-effect. However, there may also be a differential advection associated with the sheared flow that is not included in the simple beta-effect. Shear in the basic current may also damp or intensify the tropical disturbance depending on the conversion of mean to eddy kinetic energy, although it is not clear whether this affects the motion.

A long-range result of this research initiative may be to specify how much of the present error in track forecasts is due to poor understanding of physical mechanisms versus our inability to measure/forecast the "steering flow". The problem is that we presently cannot separate the sources of these errors. Statements that 70-80% of the cyclone motion is associated with the large-scale steering flow need to be substantiated. As Bob Merrill pointed out, it would be nice to have a perfect data set to answer such questions. As described above, the steering current changes in time. We need to understand how, and with what time lag, these external changes will affect the tropical cyclone motion.

f. Cyclone-cyclone interaction. (M. DeMaria)

As indicated in Section 2, several studies of the "Fujiwhara-effect" have appeared recently. It seems useful to define an "absolute beta-effect" in which the relative vorticity of the large-scale flow pattern is added to the beta term. If two tropical cyclones are close enough to interact, the wind profile of one cyclone will become the "environment" of the other cyclone. Interpreted in this sense, the gradient of vorticity in the outer region of the cyclone will contribute to an attraction (repelling) of the other cyclone

depending on the direction of the relative vorticity gradient. Thus, the shape of the wind profile in outer regions is a crucial component in this argument.

Some questions arise from these barotropic model results. What is the effect of baroclinic (vertical shear) processes? What is the role of boundary layer or mid-level convergence of one cyclone on the other? What is the impact of the upper-level outflow of one cyclone on the intensity or motion of the other? These questions can be studied with three-dimensional models with parameterized physics.

Considering the importance of the recurvature forecast described above, can the critical separation distance between the midlatitude trough and the tropical cyclone be interpreted as in the cyclone-cyclone case? Vorticity gradients associated with midlatitude troughs may exceed the background beta-effect by a factor of five. As the tropical cyclone begins to recurve it first may be under the influence of the vorticity gradient associated with the subtropical high, and then later with the midlatitude trough. As emphasized above, the vertical shear (baroclinic) effects need to be included in this interpretation.

4. Research approaches

Discussion of key questions/issues naturally led to approaches or tools that might be utilized in future studies. Some of the questions can be addressed with existing models. Different horizontal structures of the vortex should first be examined in the barotropic, non-divergent model. In addition, other theoretical models should be explored. Roger Smith suggested that comparisons with solutions of a neutral baroclinic model might be helpful, especially for understanding vertical shear effects. Both Roger Smith and Terry Williams suggested that a generalized vortex-vortex approach might be helpful to understand the variety of influences affecting the tropical cyclone track. Finally, Joe Chi suggested that laboratory models may assist understanding of geophysical aspects.

As indicated above, the new model framework proposed by Willoughby has the potential to study a number of physical effects, e.g., wave-wave interaction, asymmetric heating distributions, beta-effect and frictional asymmetries. This model should provide further insights into the dynamics of azimuthal wave one, and thus on the tropical cyclone motion.

A combination of observations and simple dynamical models may be appropriate in some cases. For example, the simple advective or beta-effect models are efficient and easy to interpret. Integrating these models and comparing with actual storm tracks (or more complex dynamical model predictions) could indicate when nonlinear effects are crucial. Unfortunately, it will not always be possible to determine whether an incorrect analysis also contributed to the departure from the actual track. Nevertheless, the use of simple models, or the expected pattern based on a theoretical result, can often be useful in analyzing why the motion occurred.

Some effort should be given to understanding the adjacent synoptic and

larger scale features that affect the tropical cyclone motion. An example is the prediction of the amplitude and position of the subtropical ridge as the tropical cyclone curves around the ridge. Some case studies of the accuracy of the operational global models in these situations could illustrate the severity of the problem. While funding from this research initiative is not appropriate for efforts to improve large-scale predictions in the tropics, it would be helpful to document how such the deficiencies contribute to track errors so that other funding can be sought for this purpose.

Observational studies to explore the factors that contributed to large track forecast errors should also be pursued. Given the benefit of hindsight, forecasters can often suggest what caused the large errors. The most frequently cited cause is the lack of observations to define the changes in the steering flow. However, careful post-analysis might provide a more specific documentation of the role of the steering current versus other possible physical mechanisms.

5. Testable hypotheses with existing/future data

A number of the theoretical results can provide hypotheses that might be examined with existing data sets, or might be the focus of the field experiment during 1989. Some of the tests will naturally be performed in conjunction with the ongoing theoretical studies. In other cases, specific data sets will have to be prepared. It is critical that these observational studies proceed rapidly so that possible scenarios and data distribution requirements can be addressed in the design of the field experiment.

a. Definition of cyclone and environment.

The proposal (Section 3a) for separating the flow into three components (symmetric cyclone; background flow; asymmetric cyclone structure) should be addressed with aircraft reconnaissance in the Pacific region and with composite rawinsonde data sets. Use of different filtering techniques should be explored to define a background flow that includes horizontal shear. Alternatively, a uniform background flow equal to the track direction and speed should be removed. Special focus should be on extracting a signal comparable to the pattern in Fig. 1c. If this pattern does appear, the orientation of the pattern should be aligned with the deviation of the storm motion from the background flow (expected magnitudes of 0.5-1.5 m/s). The motion variance not associated with the background flow should be in proportion to the amplitude of the nonlinearities (± 2.5 m/s). Stratifications for different storm directions should be attempted, especially relative to the time of recurvature. Stratifications by size of the cyclone, or other storm-related factors, are also desirable. Finally, cases with clearly defined asymmetries in convection should be examined separately.

b. Beta-effect studies.

Deviations of the tropical cyclone motion from the large-scale

steering should be a function of the shape of the wind profile and the "strength" of the outer region winds. These effects can be tested with the reconnaissance data in the Pacific region.

Cases of tropical cyclones "punching through" the subtropical ridge should be related to the propagation component associated with the beta-effect. For example, storms with greater "strength" should propagate more rapidly through subtropical ridges with similar horizontal scales.

c. Form of the vortex.

Larger (smaller) northward deviations in the storm motion should be found with more cyclonic (anticyclonic) relative angular momentum profiles. The net zero relative angular momentum profile should be a "natural" profile.

Sequences of dynamical model track forecasts with wind profiles replicating actual storm characteristics should provide better overall guidance than forecasts with dissimilar storm characteristics. A partial verification of this statement has been demonstrated by Chan et al. (1986) with the Nested Tropical Cyclone Model.

d. Environmental structure effects.

For the same average wind in the column, cases with greater vertical wind shear should have larger track deviations relative to the environmental advective component. Composites of rawinsonde data or from operational wind analyses are required to calculate vertical shear, since aircraft reconnaissance is typically at a single level.

Vertical shear should be examined separately in the upper and lower troposphere. Cases with the shear concentrated in the upper troposphere (such as in the Tropical Upper Tropospheric Trough cases) should have less effect on storm motion than when the shear extends throughout the troposphere. According to R. T. Williams, a smaller beta-effect should be found with the higher order

vertical modes.

No effect on cyclone motion should occur with purely linear horizontal shear as the effect depends on $\partial^2 u / \partial y^2$. Cases with opposite curvature in the horizontal wind profiles should have opposite storm motion deviations.

Situations with large temporal variations in the large-scale flow should have larger cyclone motion deviations than cases without temporal variations. The lag in the response of the tropical cyclone motion should be proportional to the separation distance between the cyclone and the center of temporal activity.

6. Potential impacts on tropical cyclone applied research efforts

Although the purpose of this research initiative is to improve basic understanding of tropical cyclone motion, it may be useful to indicate some areas in which the results of this research might be applied. The following list is not intended to be exhaustive; rather, the purpose is simply to summarize some of the suggestions that were made at the Planning Meeting.

A better understanding of the factors involved in tropical cyclone motion can indicate where the efforts should be focused to improve operational predictions. Hopefully, a statement can be made about the limits of predictability of tropical cyclone tracks for different synoptic situations. This would be helpful in establishing the cost-benefit ratio to improve the track, and also lead to more realistic estimates of the benefits to be gained.

If it is established that the primary requirement is to improve the specification of the steering flow, a precise statement of the data requirements could assist planners in developing the observational resources. It may be possible to suggest changes in the aircraft reconnaissance tracks to obtain observations in critical areas for different synoptic situations. If it is established that improper representations of physical processes in the dynamical models significantly contribute to track uncertainties, this information should be useful guidance to model developers. Knowledge of the required horizontal and vertical resolutions to represent accurately the interaction between the vortex and the basic current (and other physical processes) will also be useful to the model developers.

One of the known deficiencies of all dynamical track prediction models is the inaccurate specification of the initial conditions in the region of the tropical cyclone. As a consequence, the storm path in the model is often poor during the early forecast period, which later may cause improper timing of such

crucial events as recurvature. The theoretical results presented at the Planning Meeting may provide a clue for improving these initial conditions. Specifically, the pattern of nonlinearities (such as in Fig. 1c) associated with the beta-effect and other physical effects must be bogused into the initial fields since it is unlikely that the observations will be accurate enough to specify this pattern. Perhaps the inclusion of this pattern will provide the initial conditions to assure a realistic early track. Hopefully, an early benefit of this research initiative will be a method for specifying these initial conditions.

Another example of improved initialization may come from the cyclone-cyclone studies. No method exists for specifying the initial conditions in these Fujiwhara situations, which often occur in the western North Pacific. As indicated above, the correct prediction of the tendency for attraction/repelling may depend on subtle changes in the wind profiles between the two cyclones. Thus, a potential benefit would result if these conditions could be derived from the theoretical and observational studies funded by this research initiative.

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APPENDIX A

PLANNING MEETING ON THEORY OF TROPICAL CYCLONE MOTION

ATTENDEES

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C.-P. Chang	Naval Postgraduate School
Simon Chang	Naval Research Lab
George Chen	National Taiwan University
Joe Chi	University of District of Columbia
Mark DeMaria	North Carolina State University
Russ Elsberry	Naval Postgraduate School
Mike Fiorino	Naval Environmental Prediction Research Facility (NEPRF)
Bill Frank	Pennsylvania State University
Bill Gray	Colorado State University
Rich Hodur	NEPRF
Greg Holland	Bureau of Meteorology (Australia)
Jerry Jarrell	Science Applications International
Henry Jones	Naval Postgraduate School
Tom Keenan	Bureau of Meteorology
John Manobianca	Florida State University
John McBride	Bureau of Meteorology
Rob Merrill	National Hurricane Center
Steve Payne	NEPRF
Melinda Peng	Naval Postgraduate School
Roger Smith	Monash University (Australia)
Ted Tsui	NEPRF
Alan Weinstein	Office of Naval Research
Terry Williams	Naval Postgraduate School
Hugh Willoughby	Hurricane Research Division (NOAA)
T.C. Yeh	Central Weather Bureau (Taiwan)

APPENDIX B

DISCUSSION QUESTIONS

1. Beta effect

What is the present status of our knowledge regarding the beta effect? How does the outer and inner structure of the cyclone change this effect? Do the observational studies agree with the present theory regarding the effects of storm size and intensity? What further work is required?

2. Definition of a steering current

Is the concept of a steering current useful for numerical model studies with vertical shear? Are the definitions of steering in the observational studies mainly for convenience, for good physical reasons, or because adequate observations do not exist to calculate stable mean values at smaller radii? Why do the observational studies of the angle between the steering and the cyclone motion seem to deviate from the numerical studies?

3. Form of the vortex

Are asymmetries in the wind circulation a cause or an effect of the tropical cyclone motion? What are the most relevant horizontal asymmetries for cyclone motion? How does the asymmetry actually affect the motion? What further work is necessary in this area? How does the divergence associated with the vortex change the motion?

4. Physical processes effect on motion

Do asymmetries in the heating in the inner-core region affect motion? Do persistent rainbands change the motion relative to the basic current? Do changes in the outer convection areas cause changes in track direction? Can these effects be tested with barotropic models? If baroclinic models are required, how will vertical shear change the effects? Does the vertical distribution of heating (shallow versus deep) affect the motion? Similarly for horizontal distribution.

What is the present understanding of the frictional effects on tropical cyclone motion? How will the PBL-convection interaction change the results of simpler frictional models? Are there important frictional effects in the outflow layer that affect motion?

5. Structure of the environment

What is the present status regarding motion effects due to horizontal and vertical shear of the environment? Is the horizontal effect primarily due to advective terms or is this interrelated to the beta effect? How are the vertical shear effects changed as a function of cyclone intensity? Do we understand the conditions in which the cyclone remains intact versus being "sheared off" by a jet aloft? Are meridional basic flows inherently less predictable situations than zonal basic flows?

6. Cyclone-cyclone interaction

What is the present status of the cyclone-cyclone interaction problem? Do we understand why a minimum separation is necessary? What is the role of divergent components? What are the primary terms in the vorticity balance? Do we understand the case in which the vortices have markedly different intensities or sizes? Are the cases of "attraction" or "repelling" understood? What further work is necessary in this area?

7. Interaction with external systems

How does the tropical cyclone "feel the effect" of an adjacent synoptic-scale circulation? Is this process primarily a horizontal effect or does it have a significant baroclinic aspect? What numerical experiments are necessary to understand the revurvature or non-recurvature problem as the tropical cyclone interacts with an extratropical system? Do similar considerations apply for interaction with a TUTT? Are there situations in which the tropical cyclone changes significantly the adjacent features (two-way interaction)?

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